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Cluster emission in superdeformed Sr isotopes in the ground state and formed in heavy-ion reaction

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Abstract. Cluster decay of superdeformed ^{76,78,80}Sr isotopes in their ground state are studied taking the Coulomb and proximity potential as the interacting barrier for the post-scission region. The predicted $T_{1/2}$ values are found to be in close agreement with those values reported by the preformed cluster model (PCM). Our calculation shows that these nuclei are stable against both light and heavy cluster emissions. We studied the decay of these nuclei produced as an excited compound system in heavy-ion reaction. It is found that inclusion of excitation energy increases the decay rate (decreases $T_{1/2}$ value) considerably and these nuclei become unstable against decay. These findings support earlier observation of Gupta *et al* based on PCM.

Keywords. Cluster decay; exotic decay.

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1. Introduction

Sandulescu *et al* [1] in 1980 first predicted cluster radioactivity, the intermediate process between alpha decay and spontaneous fission on the basis of quantum mechanical fragmentation theory (QMFT) [2]. Experimentally this phenomena was first established in 1984 by Rose and Jones [3] in the radioactive decay of ^{223}Ra by emission of ^{14}C. At present, 19 parent nuclei from ^{221}Fr to ^{242}Cm emitting clusters ranging from ^{14}C to ^{34}Si are confirmed. This cold rearrangement of large groups of nucleon from the ground state of the parent to the ground state of daughter and emitted cluster can be explained on the basis of quantum mechanical fragmentation theory.

Quantum mechanical fragmentation theory (QMFT) is able to describe cold fission, cold fusion and cluster radioactivity from a unified point of view [1,4–8]. The unifying result of this theory is the closed shell effects of one or both reaction partners for fusion or that of the decay products for fission and cluster radioactivity. In cluster radioactivity the observed daughter nuclei is always the spherical ^{208}Pb

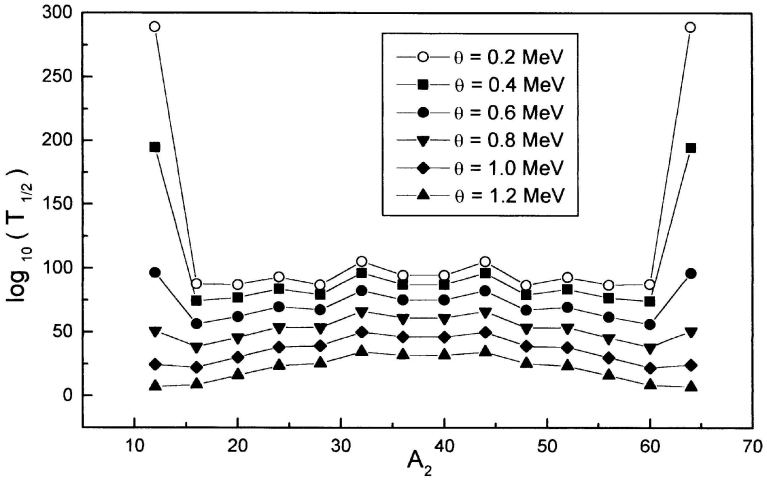

Figure 1. Variation of half-life time with nuclear temperature for various clusters from ^{76}Sr*.

or closely lying nuclei. In cold fission maximum yield is associated with spherically closed doubly magic ^{132}Sn or nearly closed shell nuclei. Cold syntheses of super heavy nuclei (cold fusion reaction) are successful with doubly magic ^{208}Pb and with ^{209}Bi projectiles [9,10]. We would like to point out that Gupta and collaborators [11,12] revealed similar phenomena with magic or nearly magic deformed nuclei in their study on the stability of deformed closed shell.

^{76}Sr, ^{78}Sr and ^{80}Sr are superdeformed nuclei, which can be produced in heavy-ion reaction [13,14] using ^{28}Si and ^{48,50,52}Cr projectiles. Within the Coulomb and proximity potential model [15] we studied the cluster decay of these nuclei in their ground state and decay of these nuclei produced as an excited compound system in heavy-ion reaction which is presented in this paper. The details of the model are given in §2 and results, discussion and conclusion are given in §3.

2. The model

The interacting barrier for a parent exhibiting exotic decay is given by

$$V = \frac{Z_1 Z_2 e^2}{r} + V_{\rm p}(z) + \frac{\hbar^2 \ell(\ell+1)}{2\mu r^2}, \quad \text{for } z > 0. \tag{1}$$

Here Z_1 and Z_2 are atomic numbers of daughter and emitted cluster, r is the distance between the fragment centers, z is the distance between the near surface of the fragments and ℓ is the angular momentum. The mass parameter is replaced by reduced mass $\mu = mA_1A_2/A$, where m is the nucleon mass and A, A_1 and A_2, represent mass numbers of the parent, daughter and emitted cluster respectively. $V_{\rm p}$ is the proximity potential given by Blocki *et al* [16]

$$V_{\rm p}(z) = 4\pi\gamma b \frac{C_1 C_2}{C_1 + C_2} \phi\left(\frac{z}{b}\right) \tag{2}$$

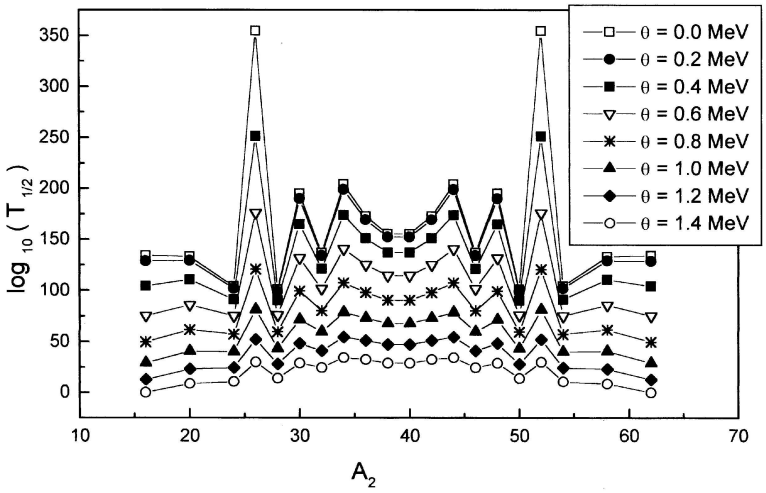

Figure 2. Variation of half-life time with nuclear temperature for various clusters from ^{78}Sr*.

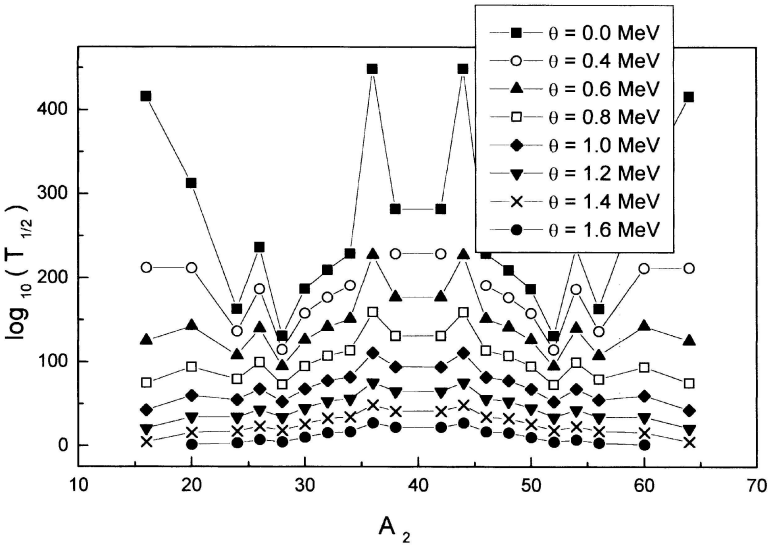

Figure 3. Variation of half-life time with nuclear temperature for various clusters from ^{80}Sr*.

with nuclear surface tension coefficient,

$$\gamma = 0.9517[1 - 1.7826(N - Z)^2/A^2]\,\text{MeV fm}^{-2}. \tag{3}$$

Here N and Z represent neutron and proton number of parent respectively. ϕ, the universal proximity potential is given as [17]

$$\phi(\varepsilon) = -4.41\text{e}^{-\varepsilon/0.7176}, \quad \text{for } \varepsilon \geq 1.9475, \tag{4}$$

$$\phi(\varepsilon) = -1.7817 + 0.9270\varepsilon + 0.01696\varepsilon^2 - 0.05148\varepsilon^3, \quad \text{for } 0 \le \varepsilon \le 1.9475, \tag{5}$$

with $\varepsilon = z/b$, where the width (diffuseness) of nuclear surface $b \approx 1$ and Siissmann central radii C_i that is related to the sharp radii R_i is $C_i = R_i - (b^2/R_i)$. For R_i we use the semi-empirical formula in terms of mass number A_i as [16]

$$R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}. \tag{6}$$

The barrier penetrability P is given as

$$P = \exp\left\{-\frac{2}{\hbar}\int_a^b [2\mu(V-Q)]^{1/2}\mathrm{d}z\right\}. \tag{7}$$

The inner and outer turning points a and b are defined as $V(a) = V(b) = Q$, where Q is the energy released.

The half-life time is given by

$$T_{1/2} = \ln 2/\lambda = \ln 2/\nu P. \tag{8}$$

Here λ is the decay constant and assault frequency, $\nu = 2E_\mathrm{v}/h$. The empirical zero-point vibration energy E_v is given as [18]

$$E_\mathrm{v} = Q[0.056 + 0.039\exp[(4-A_2)/2.5]], \quad \text{for } A_2 \ge 4. \tag{9}$$

3. Results, discussion and conclusion

^{76}Sr, ^{78}Sr and ^{80}Sr are superdeformed nuclei [19–22] with estimated quadrapole deformation, $\beta_2 = 0.35$–0.44. Due to such large ground state deformation, these nuclei are unstable against both fission and exotic decay processes. Asymmetric mass splitting is favoured for these nuclei as liquid drop fissility parameter $x = Z^2/50A$ is far less than Businaro–Gallone transition point [23,24]. ($x_\mathrm{BG} = 0.396$ for $\ell = 0$, and this value decreases as the value of ℓ increases).

Table 1 gives the half-life times and other characteristics for ground state decay of ^{76}Sr, ^{78}Sr and ^{80}Sr emitting various clusters. The predicted half life time values are found to be in close agreement with those values reported by Gupta and collaborators [25,26] using the preformed cluster model (PCM). We would like to point out that the potential used in the present model and in PCM are the same, but both the models use different formulation of proximity potential. Further, being a fission model, the present model differs from PCM by a factor P_0, the cluster formation probability [15,27]. Negative Q value for clusters with mass $A_2 < 12$ including α particle shows that these nuclei are stable against light cluster emission. Calculated half-life time values ($T_{1/2} > 10^{80}$ s) show that these nuclei are also stable against heavier clusters with mass $A_2 \ge 12$. The reason for this kind of stability of ^{76}Sr is due to the stable deformed shell closure at $N = Z = 38$ which supports the earlier predictions [19,28] and for that of ^{78}Sr is due to the stable deformed shell closure at

Table 1. Calculated half-life time and other characteristics for the decay of ^{76}Sr, ^{78}Sr and ^{80}Sr from its ground state.

						$\log_{10}(T_{1/2})$	
Parent nuclei	Emitted cluster	Daughter nuclei	Q value (MeV)	Penetrability P	Decay constant λ	Present	PCM [25,26]
^{76}Sr	^{12}C	^{64}Ge	0.035	2.1969E-1329	2.1416E-1311	1310.5	1315.8
	^{16}O	^{60}Zn	4.53	2.1699E-111	2.6774E-91	90.41	87.15
	^{20}Ne	^{56}Ni	6.55	2.9174E-110	5.1811E-90	89.13	87.25
	^{24}Mg	^{52}Fe	7.87	4.0321E-116	8.5958E-96	94.91	96.02
	^{28}Si	^{48}Cr	9.92	1.3138E-109	3.5297E-89	88.29	87.62
	^{32}S	^{44}Ti	9.18	2.0994E-128	5.2195E-108	107.10	106.77
	^{36}Ar	^{40}Ca	10.69	1.8355E-117	5.3140E-97	96.12	95.97
^{78}Sr	^{16}O	^{62}Zn	2.89	4.6397E-155	3.6521E-135	134.28	137.37
	^{20}Ne	^{58}Ni	4.25	2.7325E-154	3.1488E-134	133.34	140.97
	^{24}Mg	^{54}Fe	7.16	1.3435E-125	2.6058E-105	104.43	114.29
	^{26}Mg	^{52}Fe	1.52	1.6549E-375	6.8134E-356	355.01	357.06
	^{28}Si	^{50}Cr	8.73	1.4069E-122	3.3264E-102	101.32	112.07
	^{30}Si	^{48}Cr	4.23	2.5132E-216	2.8792E-196	195.38	202.70
	^{32}S	^{46}Ti	7.13	3.4158E-158	6.5957E-138	137.02	147.56
	^{34}S	^{44}Ti	4.46	2.9158E-225	3.5219E-205	204.29	214.11
	^{36}Ar	^{42}Ca	5.76	3.9609E-194	6.1788E-174	173.05	184.32
	^{38}Ar	^{40}Ca	6.55	1.1123E-176	1.9731E-156	155.54	167.27
^{80}Sr	^{16}O	^{64}Zn	0.55	5.5827E-436	8.3632E-417	415.92	415.90
	^{20}Ne	^{60}Ni	1.33	7.5674E-333	2.7289E-313	312.41	318.52
	^{24}Mg	^{56}Fe	4.35	3.2416E-184	3.8198E-164	163.26	177.20
	^{26}Mg	^{54}Fe	2.75	3.1732E-257	2.3635E-237	236.47	249.60
	^{28}Si	^{52}Cr	6.71	2.4776E-152	4.5026E-132	131.19	146.67
	^{30}Si	^{50}Cr	4.50	7.4669E-208	9.1001E-188	186.88	188.55
	^{32}S	^{48}Ti	4.31	3.2396E-230	3.7814E-210	209.26	223.60
	^{34}S	^{46}Ti	3.87	7.2582E-250	7.6072E-230	228.96	244.25
	^{36}Ar	^{44}Ca	1.51	2.9634E-469	1.2118E-449	448.76	462.48
	^{38}Ar	^{42}Ca	3.07	9.8580E-303	8.1961E-283	281.93	298.11

$Z = 38$ and the spherical/deformed shell closure at $N = 40$. It is found that ^{78}Sr is more stable than ^{76}Sr and ^{80}Sr is more stable than ^{78}Sr. The role of Q value is also reflected in table 1. Smaller Q value results in smaller penetrability P (smaller decay constant λ). This makes ^{80}Sr more stable than ^{78}Sr and ^{76}Sr. These findings based on the present fission model support the earlier observation of Gupta and collaborators [25] based on the preformed cluster model.

If a nucleus is formed in a heavy-ion reaction, depending on the excitation energy and angular momentum, the excited compound nucleus undergo fission (also called fusion–fission), decay via cluster emission or result in resonance phenomena (dinuclear orbiting). The light compound system with $A \leq 42$ and the heavier one with $A \geq 64$ would go through orbiting and fission [29,30].

Table 2. Calculated half-life time and other characteristics for the decay of excited compound system ^{76}Sr*, ^{78}Sr* and ^{80}Sr*. Nuclear temperature θ of the compound system is arbitrarily taken as 1.2 MeV for ^{76}Sr*, 1.4 MeV for ^{78}Sr* and ^{80}Sr*.

Parent nuclei	Emitted cluster	Daughter nuclei	E^* (MeV)	Q value (MeV)	$Q_{\rm eff}$ (MeV)	Penetrability P	Decay constant λ	$\log_{10}(T_{1/2})$ Present
^{76}Sr*	^{12}C	^{64}Ge	10.96	0.035	10.995	1.4697E-28	4.5006E-08	7.19
	^{16}O	^{60}Zn		4.53	15.49	2.2170E-30	9.3536E-10	8.87
	^{20}Ne	^{56}Ni		6.55	17.51	5.5043E-38	2.6132E-17	16.42
	^{24}Mg	^{52}Fe		7.87	18.83	2.4517E-45	1.2505E-24	23.74
	^{28}Si	^{48}Cr		9.92	20.88	3.0776E-47	1.7404E-26	25.60
	^{32}S	^{44}Ti		9.18	20.14	3.7204E-56	2.0293E-35	34.53
	^{36}Ar	^{40}Ca		10.69	21.65	1.0747E-53	6.3015E-33	32.04
^{78}Sr*	^{16}O	^{62}Zn	15.59	2.89	18.48	9.7616E-22	4.9126E-01	0.15
	^{20}Ne	^{58}Ni		4.25	19.84	2.3124E-30	1.2437E-09	8.75
	^{24}Mg	^{54}Fe		7.16	22.75	1.4281E-32	8.7996E-12	10.90
	^{26}Mg	^{52}Fe		1.52	17.11	8.5724E-52	3.9719E-31	30.24
	^{28}Si	^{50}Cr		8.73	24.32	5.2023E-36	3.4327E-15	14.31
	^{30}Si	^{48}Cr		4.23	19.82	1.0816E-50	5.8047E-30	29.08
	^{32}S	^{46}Ti		7.13	22.72	1.9299E-46	1.1873E-25	24.77
	^{34}S	^{44}Ti		4.46	20.05	3.7094E-56	2.0138E-35	34.54
	^{36}Ar	^{42}Ca		5.76	21.35	2.7218E-54	1.5735E-33	32.64
	^{38}Ar	^{40}Ca		6.55	22.14	1.8558E-51	1.1126E-30	29.14
^{80}Sr*	^{16}O	^{64}Zn	16.02	0.55	16.57	1.8384E-26	8.2979E-06	4.92
	^{20}Ne	^{60}Ni		1.33	17.35	1.0448E-37	4.9156E-17	16.15
	^{24}Mg	^{56}Fe		4.35	20.37	3.4825E-39	1.9218E-18	17.56
	^{26}Mg	^{54}Fe		2.75	18.77	7.3066E-45	3.7149E-24	23.27
	^{28}Si	^{52}Cr		6.71	22.73	3.5898E-40	2.2101E-19	18.50
	^{30}Si	^{50}Cr		4.50	20.52	1.1990E-47	6.6640E-27	26.02
	^{32}S	^{48}Ti		4.31	20.33	1.7578E-54	9.6789E-34	32.85
	^{34}S	^{46}Ti		3.87	19.89	2.3482E-56	1.2650E-35	34.74
	^{36}Ar	^{44}Ca		1.51	17.53	3.1966E-70	1.5177E-49	48.66
	^{38}Ar	^{42}Ca		3.07	19.09	4.6441E-63	2.4012E-42	41.46

The barrier penetrability P for the excited compound system is given as

$$P = \exp\left(-\frac{2}{\hbar}\int_a^b \sqrt{2\mu(V - Q_{\rm eff})}\mathrm{d}z\right), \tag{10}$$

where the effective Q value,

$$Q_{\rm eff} = Q + E^*. \tag{11}$$

The excitation energy E^* is related to the nuclear temperature θ in MeV [31] and is given as

$$E^* = \frac{1}{9}A\theta^2 - \theta. \tag{12}$$

The half-life time and other characteristics for the decay of excited compound system $^{76}Sr^*$, $^{78}Sr^*$ and $^{80}Sr^*$ formed in heavy-ion reactions are given in table 2. In our calculation, angular momentum ℓ is taken as zero since its contribution to the structure of yields is shown to be small for lighter systems [32]. Figures 1–3 give the variation of half-life time with nuclear temperature for various clusters from these compound systems. It is clear from these plots that the inclusion of excitation energy increases the decay rate (decreases $T_{1/2}$ value) considerably and these nuclei become unstable against decay. These findings support the earlier observation of Gupta *et al* [8] based on PCM.

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